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THERMAL & FLUIDS ANALYSIS WORKSHOP

GSFC · 2015

Aerothermal Considerations for Entry, Descent, and Landing

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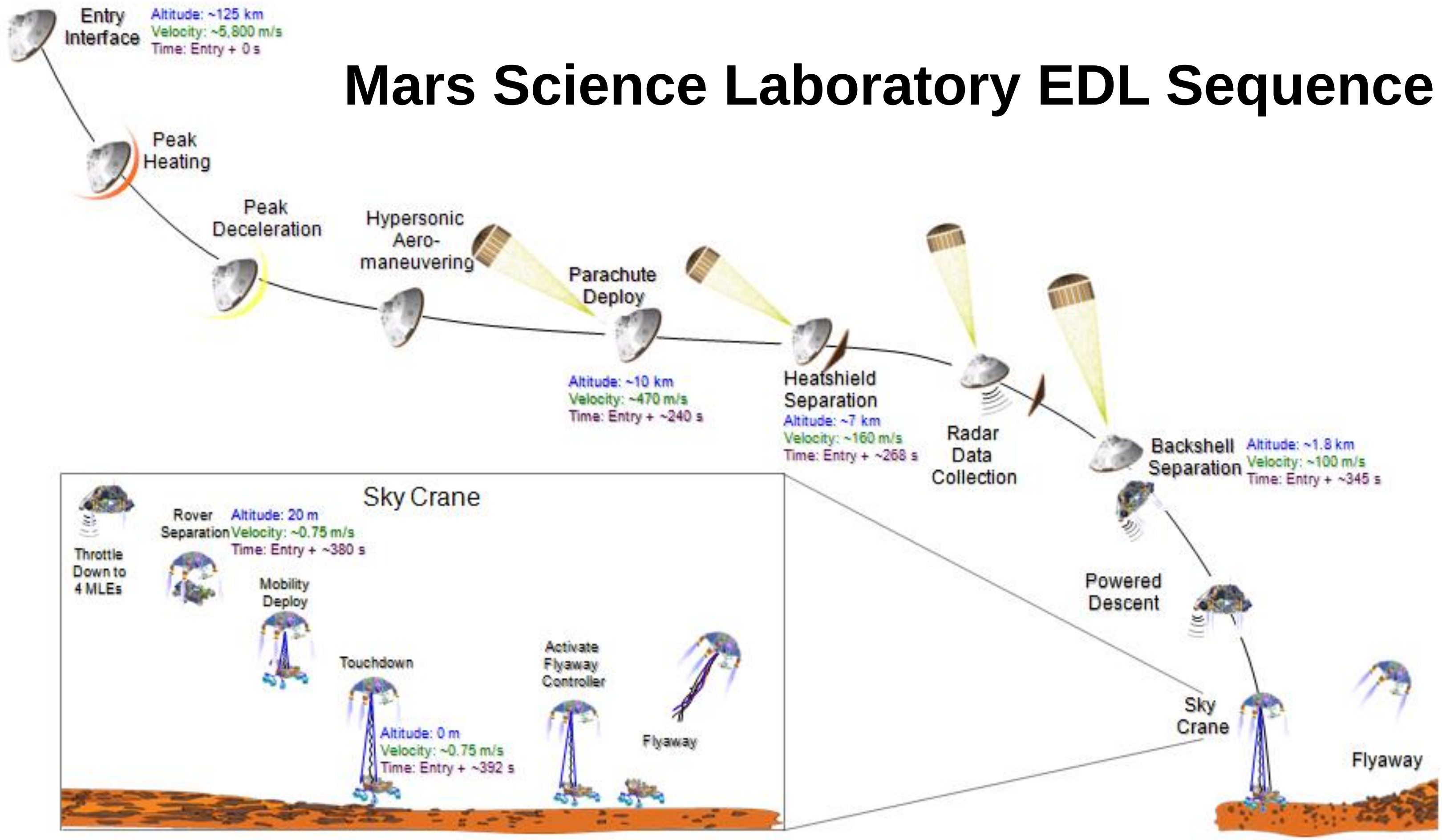
What is Aerothermodynamics?

- **Accurate and conservative prediction of the heating environment encountered by an Earth or planetary entry vehicle**

- **Aerothermal modeling is completely coupled and entwined with Thermal Protection System (TPS) design**
  - **The TPS is designed to withstand the predicted environment with risk-appropriate margin**
  - **The flowfield and TPS interact with each other in non-reversible manner; the physics themselves are coupled**

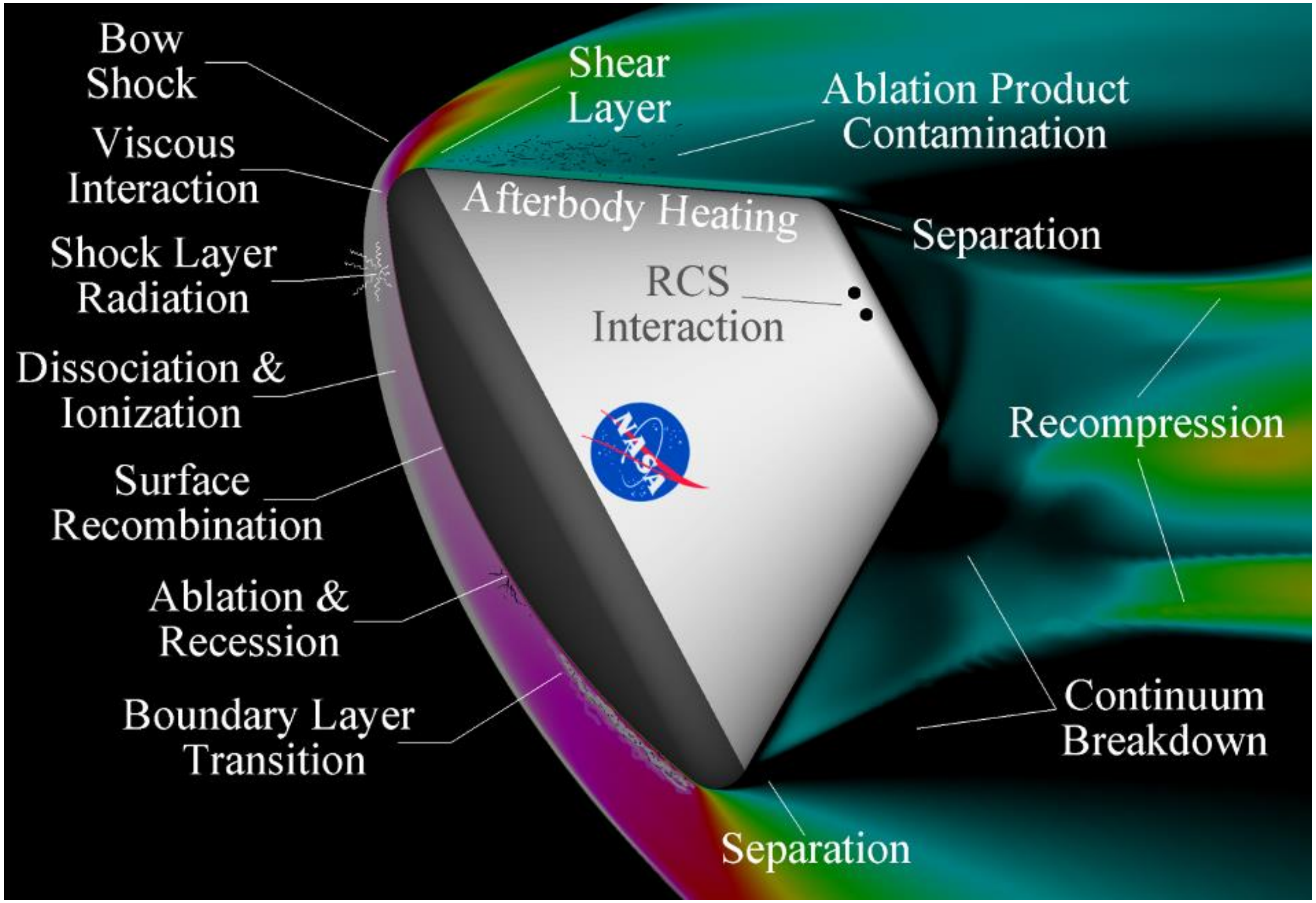
- **At its core, aerothermodynamics becomes the study of an energy balance at the surface of the material**
  - **Experimental - ground and flight testing**
  - **Engineering approximations and theory**
  - **Computational fluid dynamics (*DPLR* tutorial later this afternoon)**
  - **Shock layer radiation transport**
  - **Direct Simulation Monte-Carlo for rarified flows**

Entry, Descent, and Landing



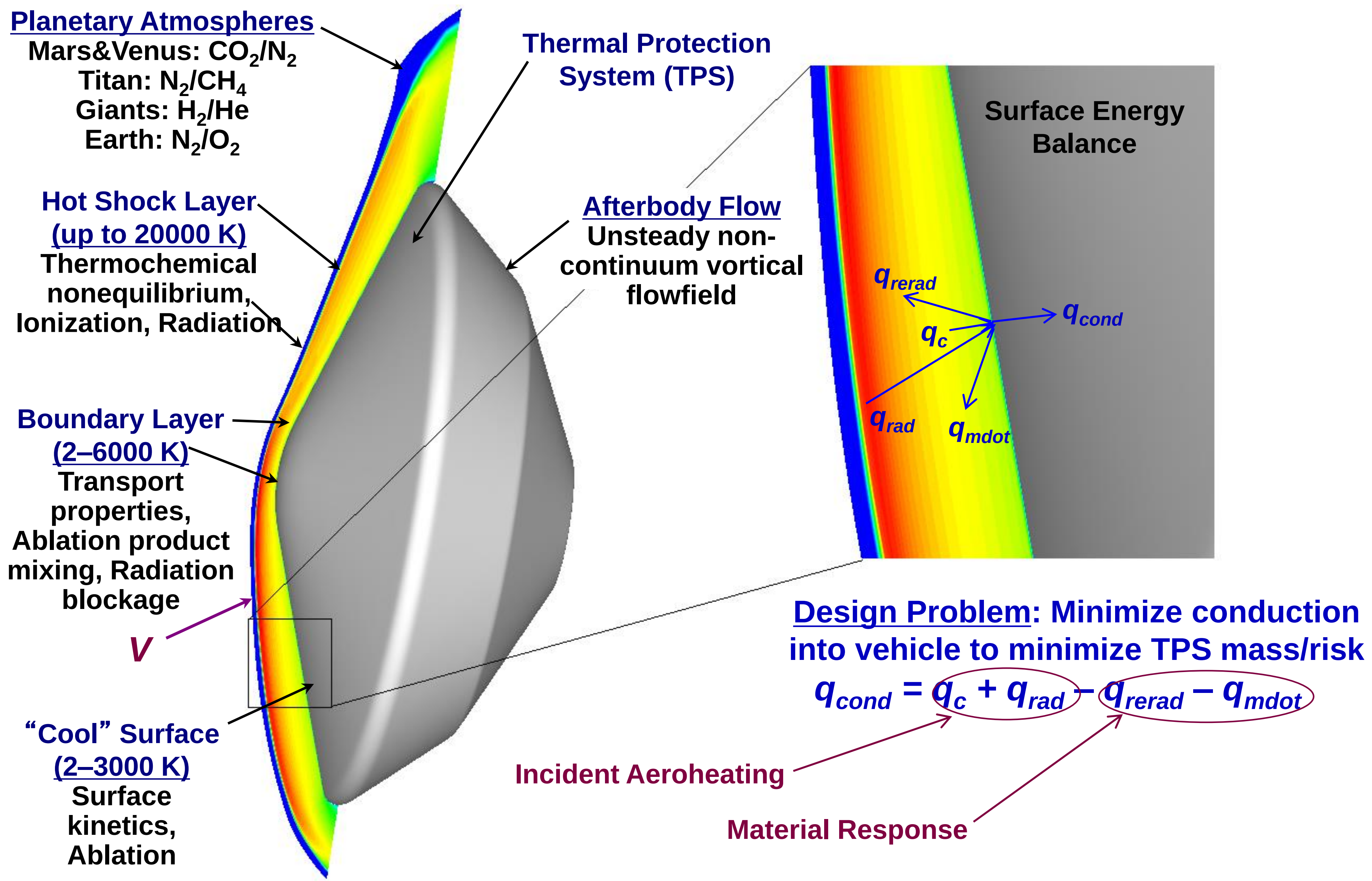
- ◆ **Aerothermal modeling and TPS design is mission specific**
- ◆ **Many factors can affect the peak heating and heat load of a spacecraft**
  - **Trajectory (velocity, density, flight path angle, …),**
  - **Vehicle (geometry, mass, angle of attack, …)**
  - **Atmospheric variations (dust, winds, …)**

Flow Physics during Entry



- Flow physics are coupled, but it's difficult to test or model all the interactions simultaneously
- To simplify the analysis, modeling of aerothermal, radiation, and TPS material response are usually done separately. Be sure to check if this simplification is valid for the mission.

Principles of Aerothermal Models



Why is Aerothermal Modeling Important?

- **Heat flux (with pressure & shear) used to select TPS material**
- **Heat load determines TPS thickness**

Can’t we just ‘cover up’ uncertainties in aerothermal modeling with increased TPS margins?

- **Sometimes, <u>but</u>:**
  - **Margin increases mass; ripple effect throughout system**
  - **Without a good understanding of the environment risk cannot be quantified; benefits of TPS margin cannot be traded with other risk reduction strategies**
  - **Margin cannot retire risk of exceeding performance limits**
  - **For some missions (i.e. Neptune aerocapture, Jupiter polar probe), improved aerothermal models may be enabling**

Can’t we retire all uncertainties via testing?

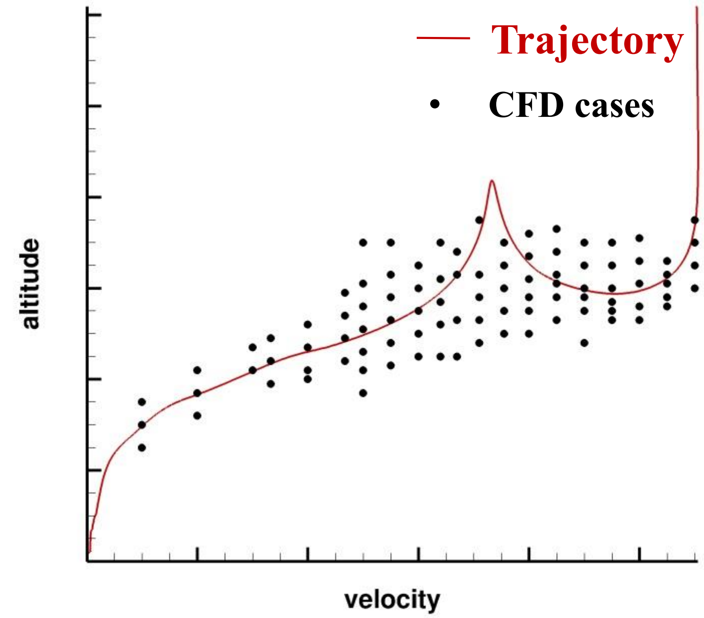
- **No!**
  - **No ground test can simultaneously reproduce all aspects of the flight environment. A good understanding of the underlying physics is required to trace ground test results to flight.**
  - **Flight testing should be reserved for model and system validation, after we have good physics-based models of the expected environment**

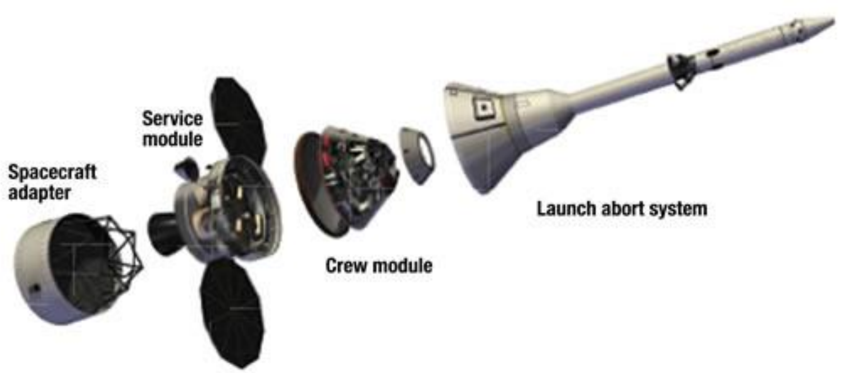
Estimating the Aerothermal Environment

- **Engineering and CFD codes are routinely used to predict the aerothermal environment using conservative assumptions: fully turbulent flow (may not be conservative for separated flows); fully catalytic wall; …**

- **To facilitate aerothermal/TPS analysis, aerothermal databases are generated to study various entry conditions (Mach, altitude) and vehicle properties (angle of attack, ballistic coefficient $\beta = m/\{C_D A\}$)**

- **Ground and flight tests used to validate aerothermal, radiation, and material response models**



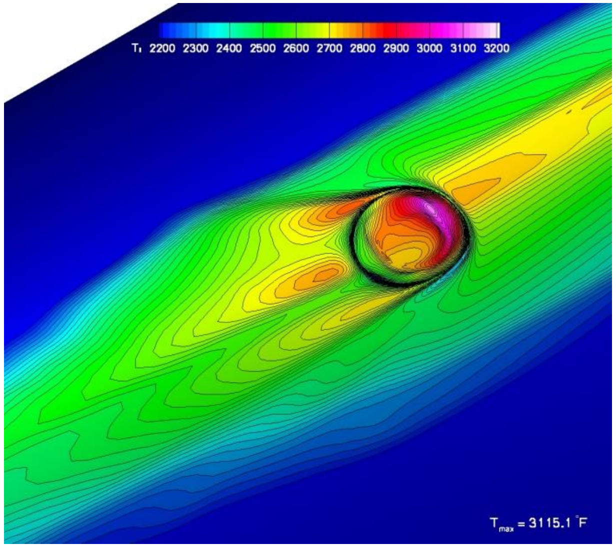


CFD Simulations for Aerothermal Analysis

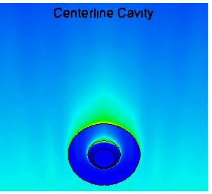
- Recent advances in parallel computing, efficient implicit algorithms have enabled rapid turnaround capability for complex geometries

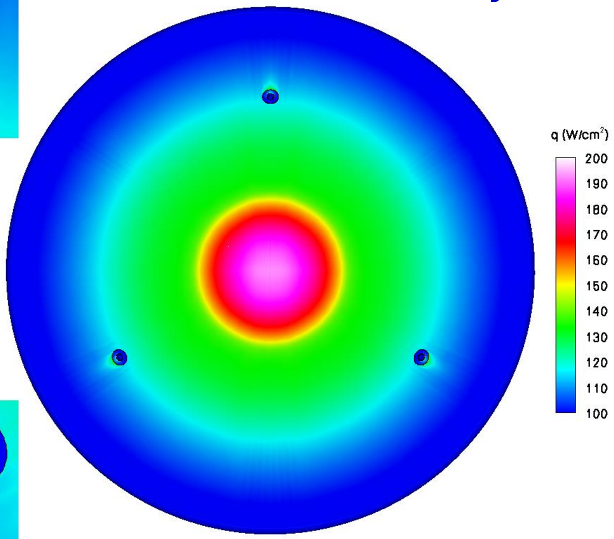
- Full body three-dimensional CFD is an integral part of the design of all planetary and Earth entry TPS

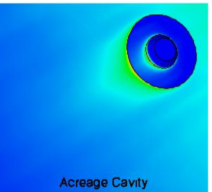
Shuttle RCC Repair Concept Evaluation



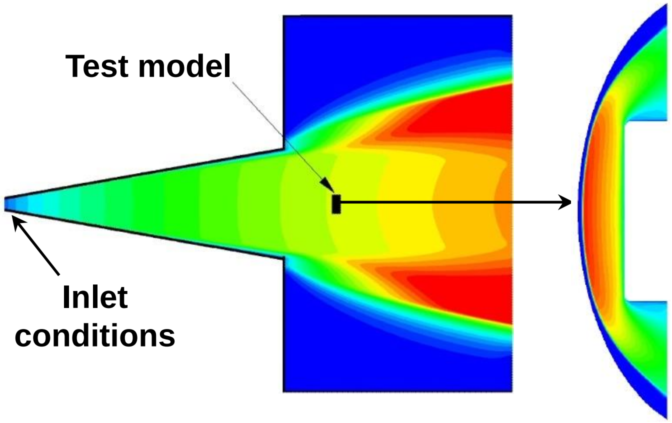
Genesis Penetration Analysis

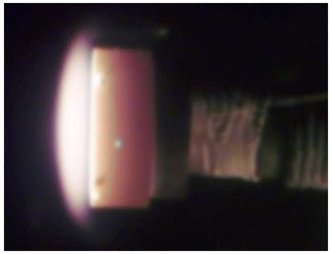






Arc Jet Model Simulation



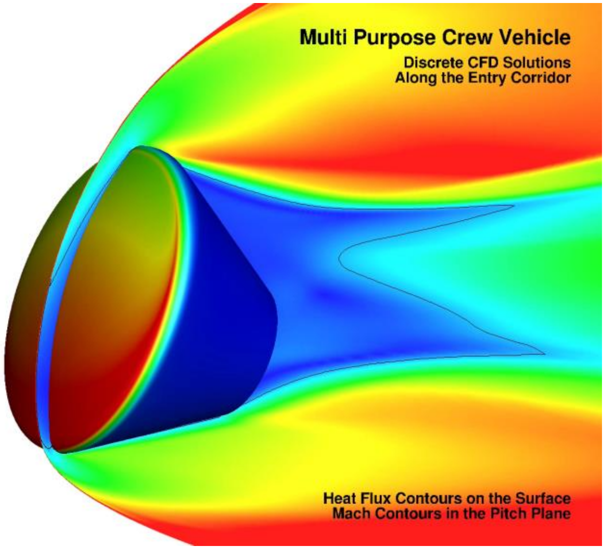


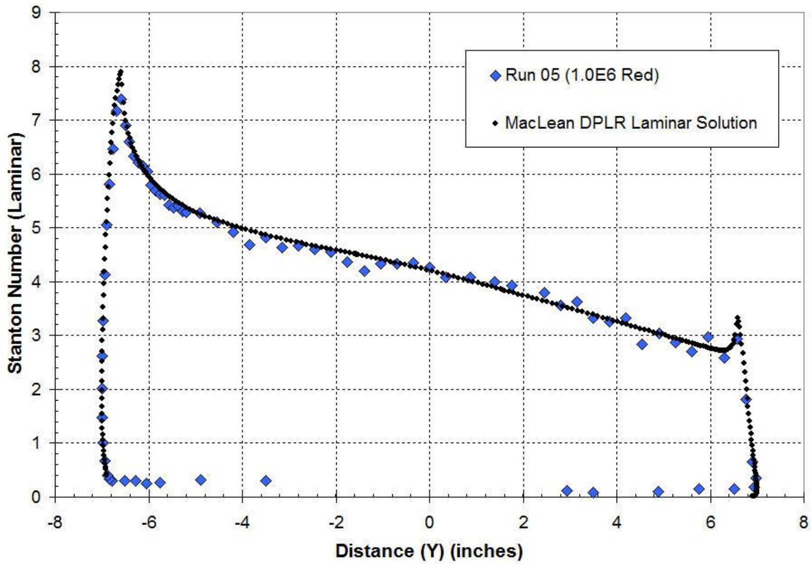
Nozzle flow CFD simulation

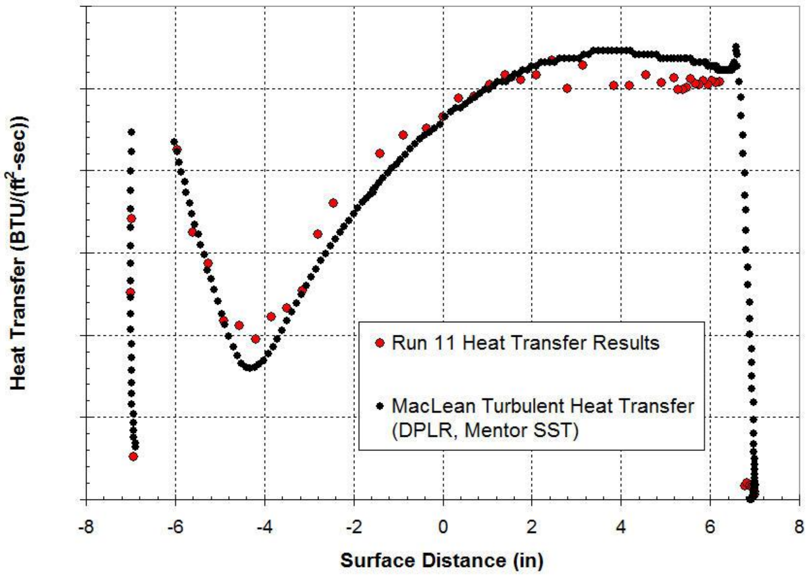
Model CFD simulation

Arc jet test

Tests to Validate Aerothermal Models on Smooth OML



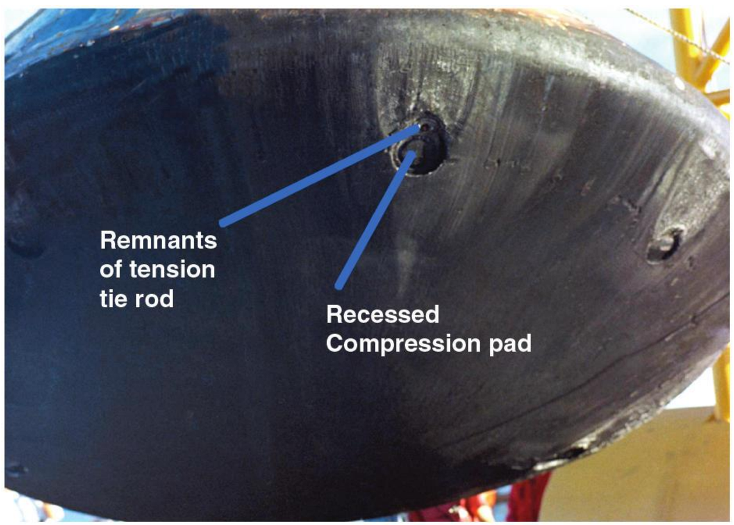




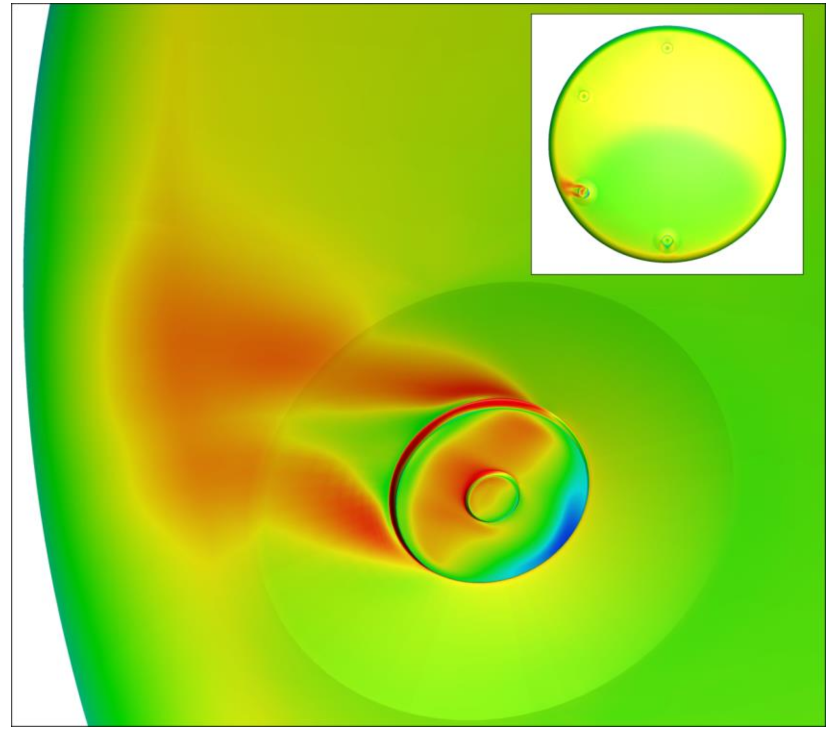
AIAA 2009-677

Compression Pad Simulations

Orion MPCV heat shield

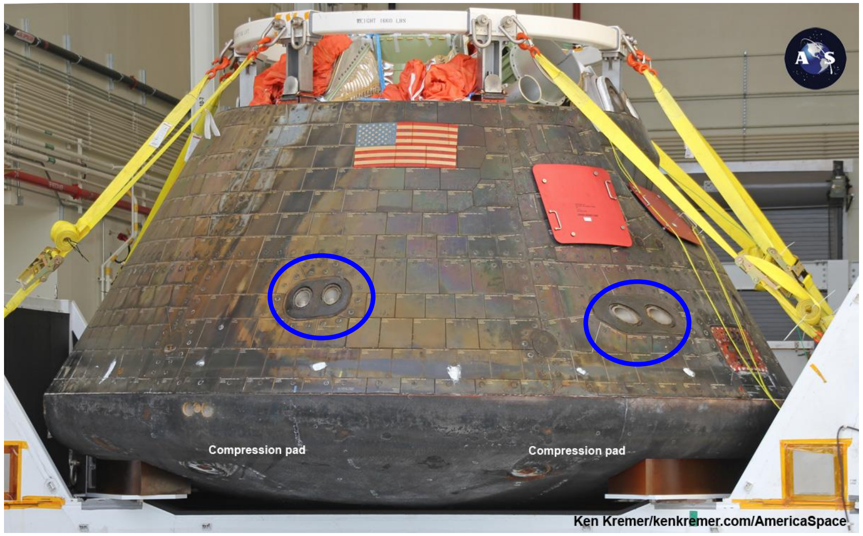


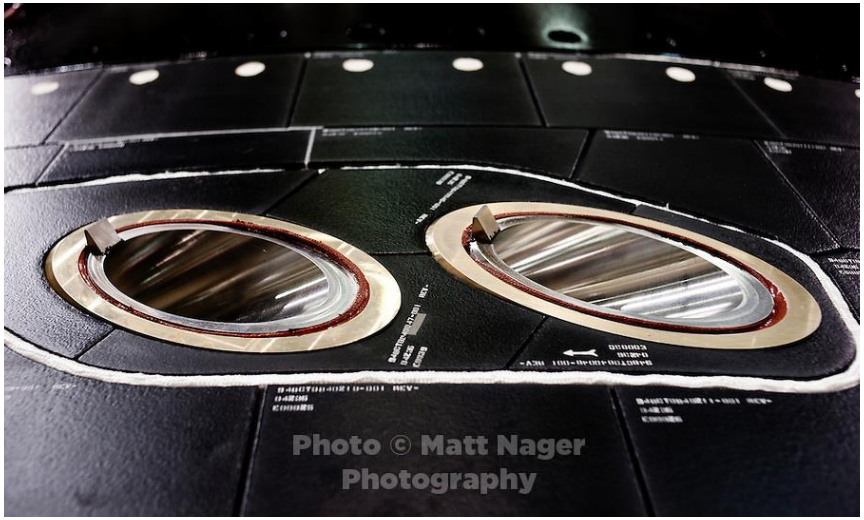
Apollo heat shield

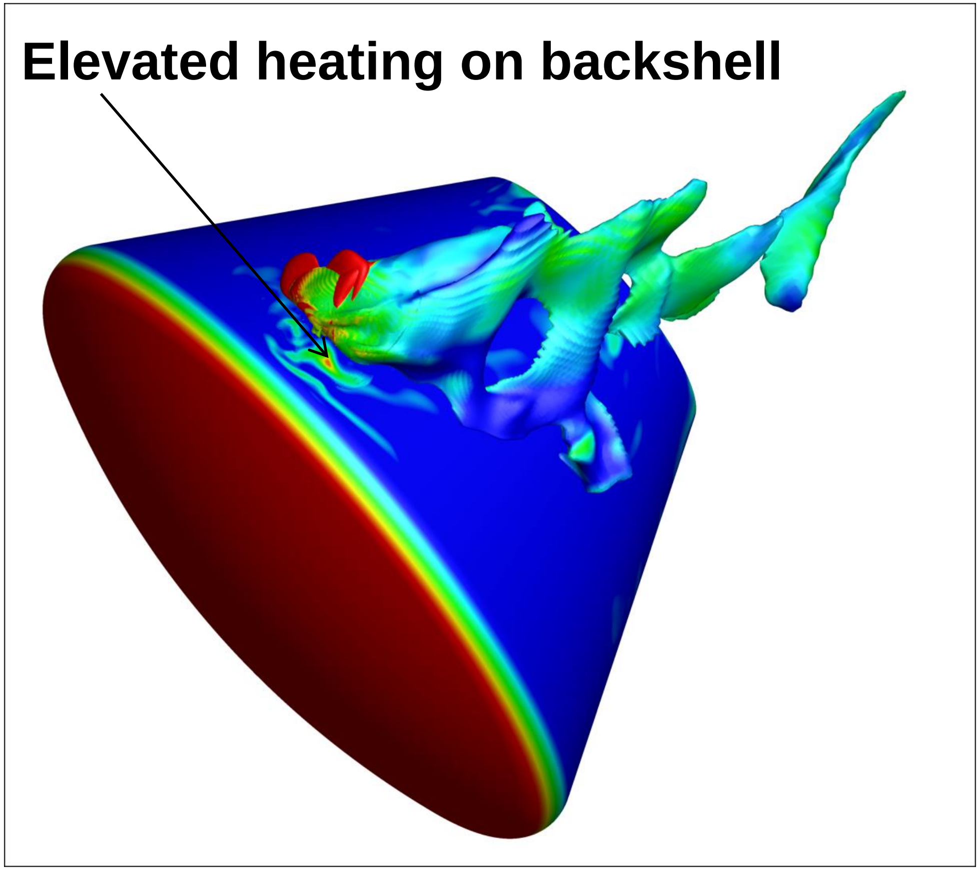


CFD simulations of complex geometries provide useful insights of potentially higher surface heating

Reaction Control System (RCS) Jet Interactions



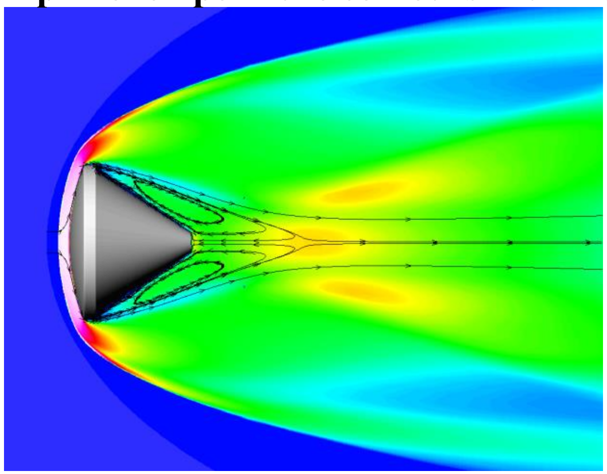




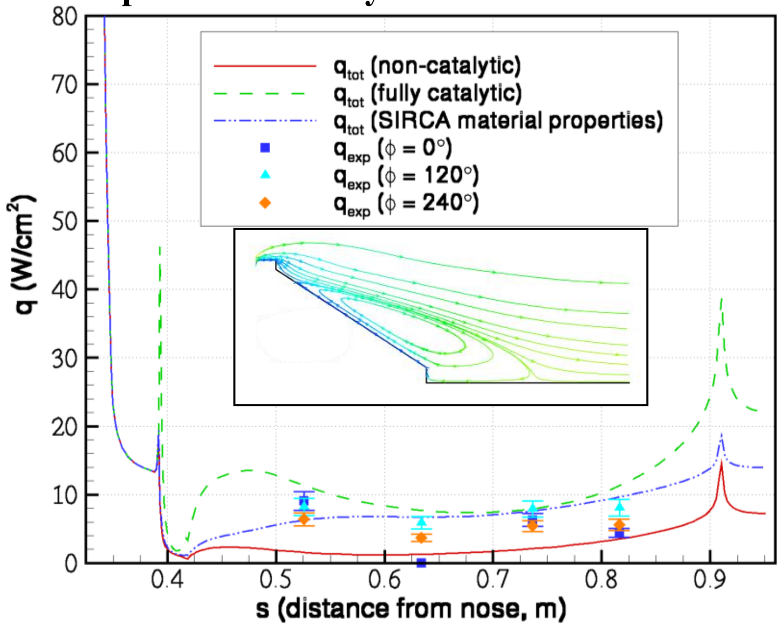
CFD simulations show possible hot spots on the backshell due to RCS interactions with the flowfield

Surface Catalysis Validation

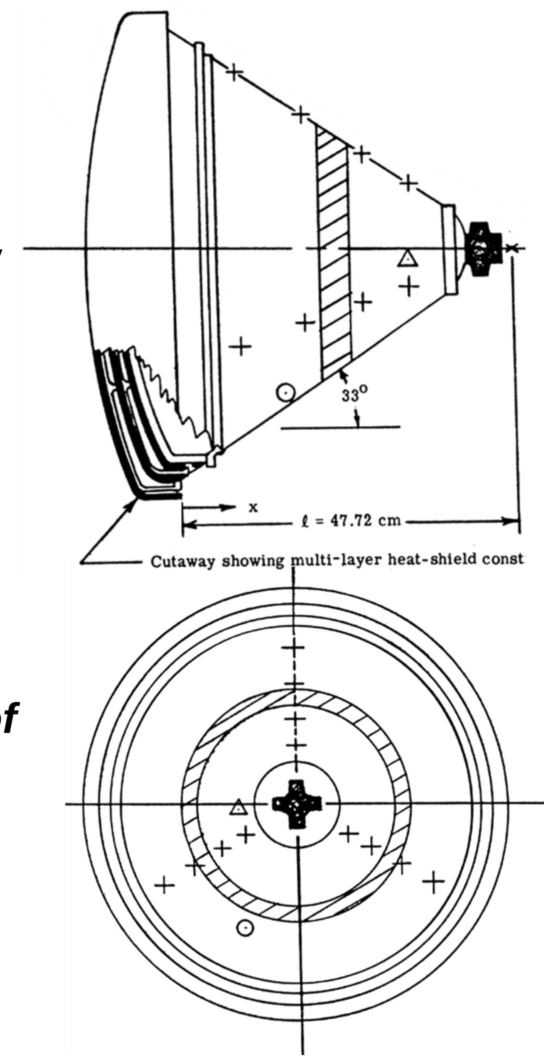
Pitch plane temperature contours at *t* = 1634 s



Computed Afterbody Heat Transfer at t=1634s



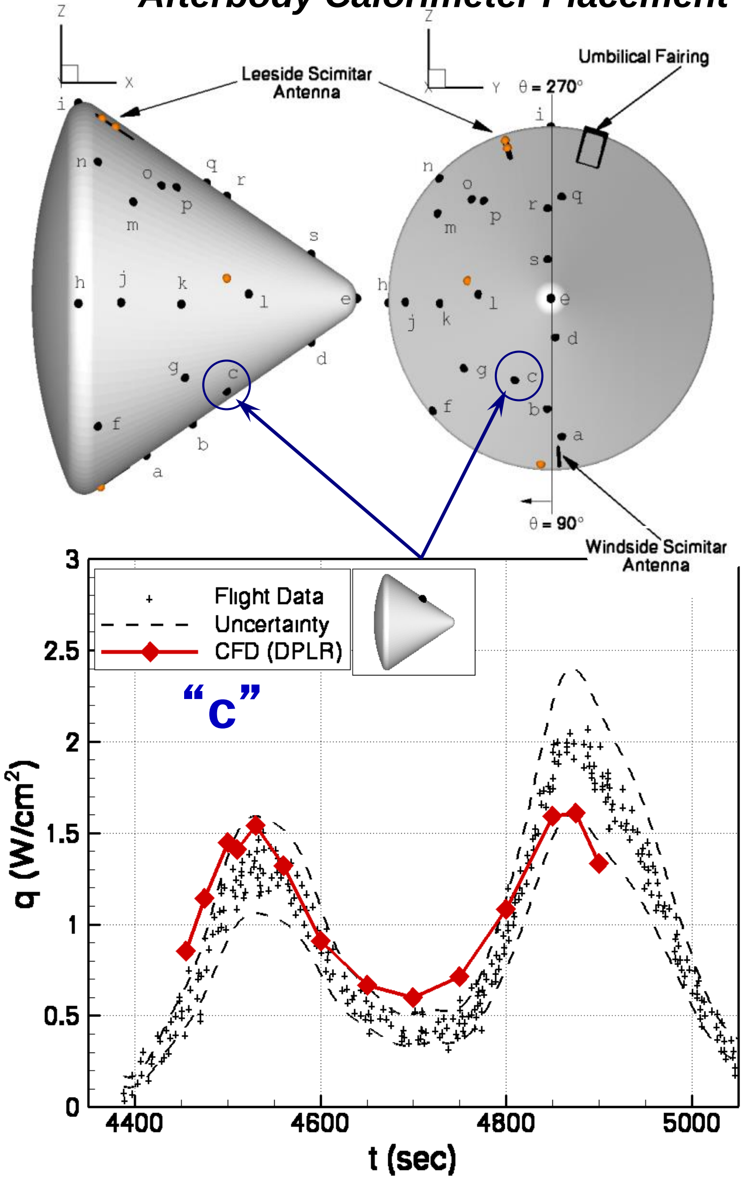
Fire-II Instrumentation



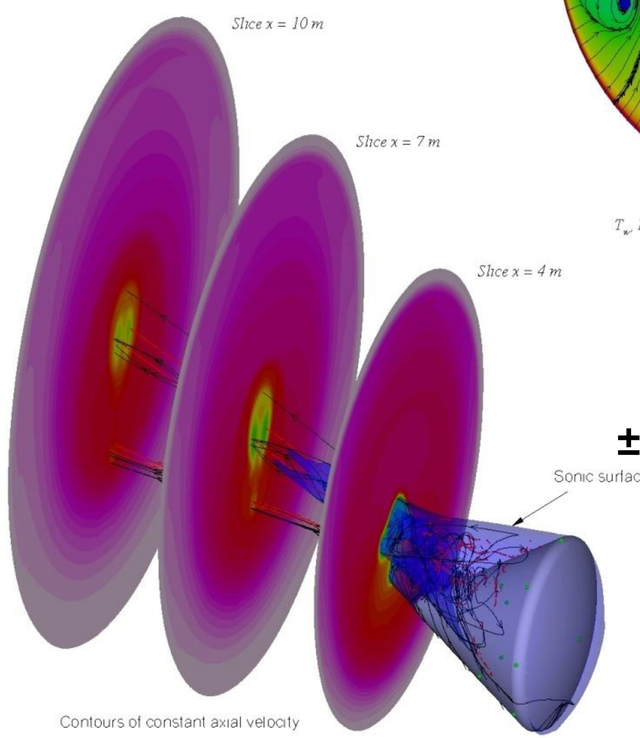
- **Goal: reduce uncertainty levels by validation with flight data**
- **Excellent agreement between CFD and flight data for laminar flows without afterbody TPS blowing**
- **Published: *Journal of Thermophysics and Heat Transfer*, Vol. 17, No. 2, 2003**

Afterbody Heating Apollo AS-202: Validation with Flight Data

Afterbody Calorimeter Placement

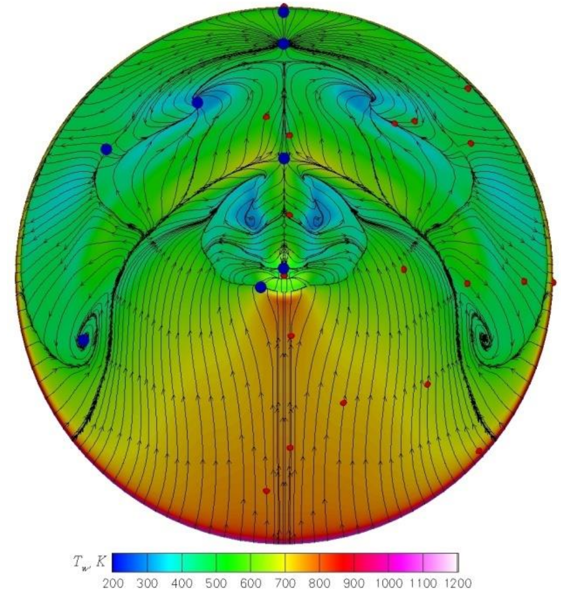


- **Problem**: Current uncertainty on afterbody heating predictions is very high
- **Goal**: reduce uncertainty levels by validation with flight data



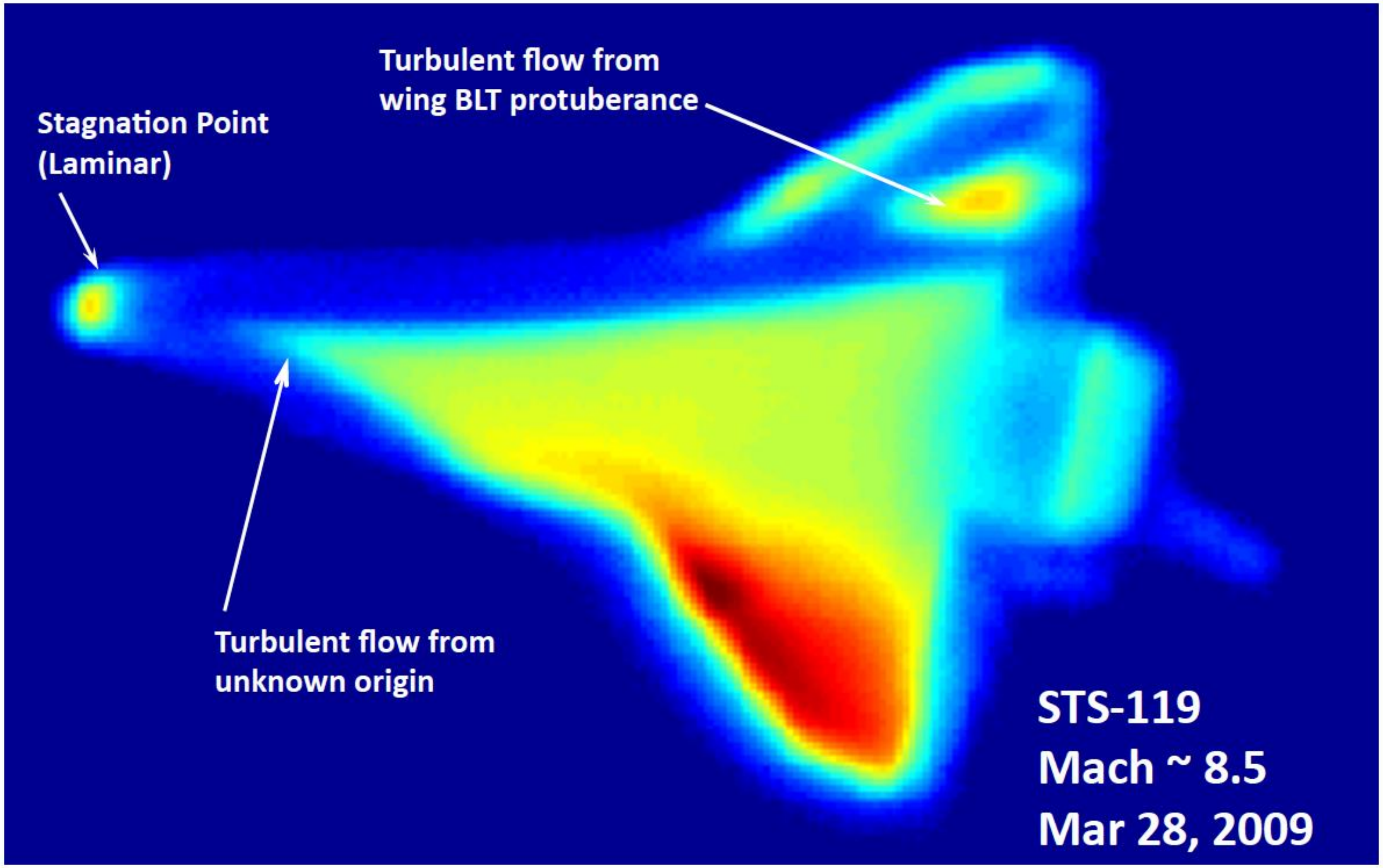
AIAA 2004-2456

Surface Oilflow
$t = 4900$ s, $Re_D = 7.6\times10^5$



⇒Computations generally agree with flight data to within ±20% uncertainty at 15 of 19 calorimeter locations.

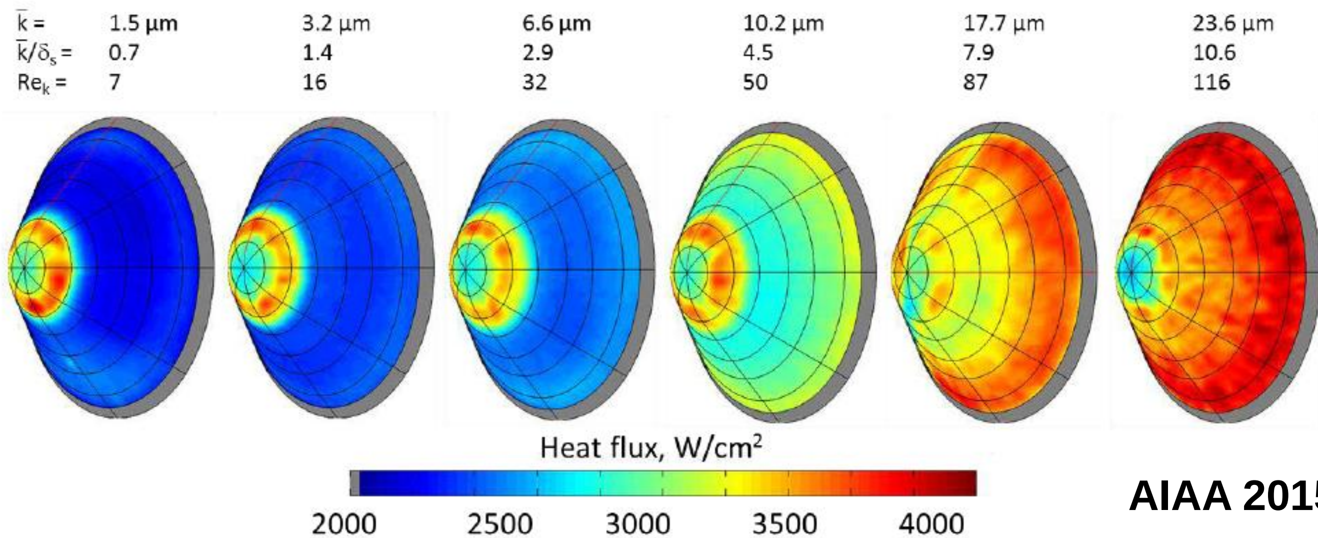
Transition and Turbulence



- Methods to predict accurate flow transition is an active area of research (methods based on Re_θ, Re_{kk}, …)
- Surface roughness (discrete and distributed) and TPS outgassing affect transition

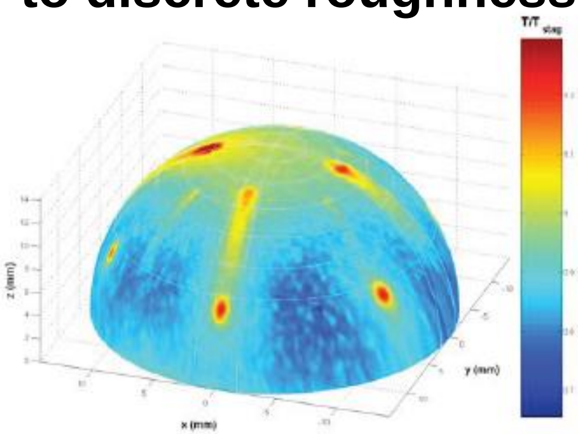
Transition Measurements in Ballistic Range

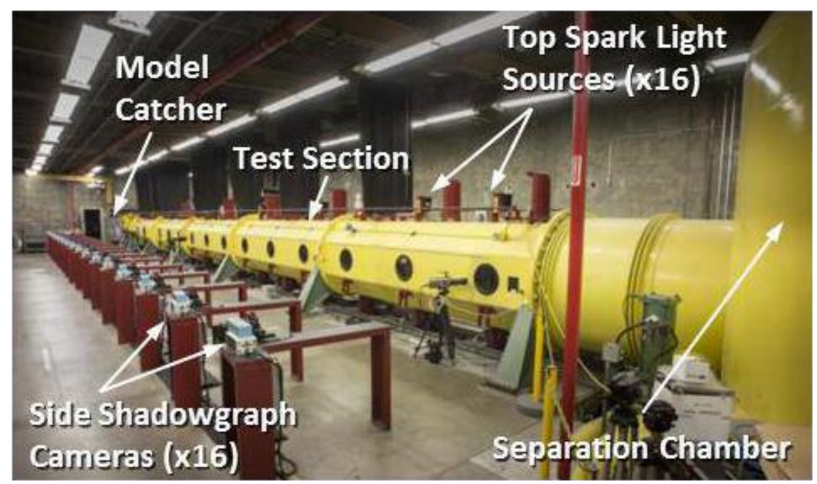
Transition measurements due to distributed roughness



AIAA 2015-1339

Transition measurements due to discrete roughness





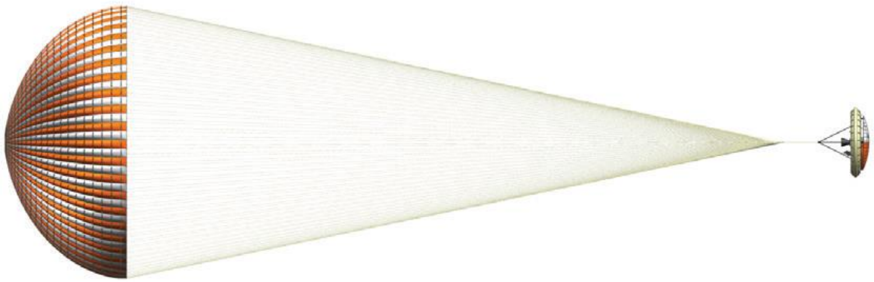
Margin Policy

- Need to develop a risk-appropriate margin policy without being overly conservative
  - How to combine/stack margins from different models?
  - A policy that is too conservative may result in excess weight, cost, and reduced payload capabilities

- Many sources of uncertainties
  - Trajectory dispersion
  - Surface kinetics (catalysis, ablation)
  - Variation in material properties
  - Effects of TPS ablation on radiation
  - Flow transition modeling
  - Turbulence model for separated flow (RANS suitable?)
  - Shock layer radiation in non-Earth entries
  - Ground-to-Flight traceability

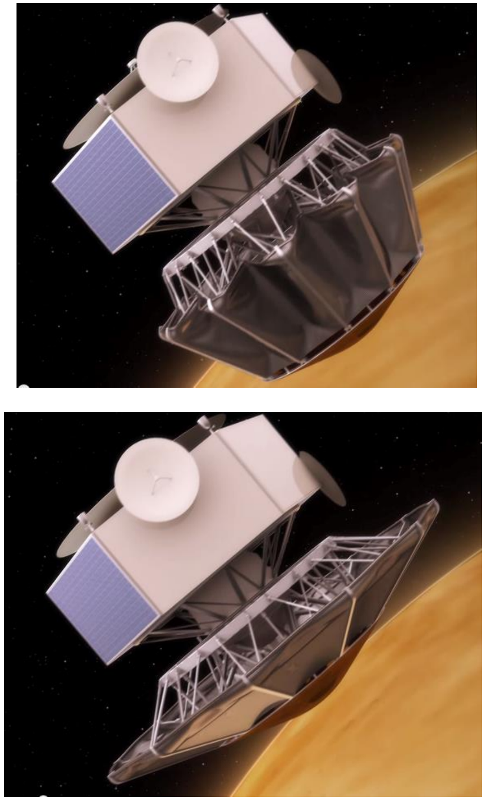
- Current margin policy uses statistical methods (Monte-Carlo) and a root-sum-square (RSS) approach [AIAA 2011-3757]

New EDL Technologies

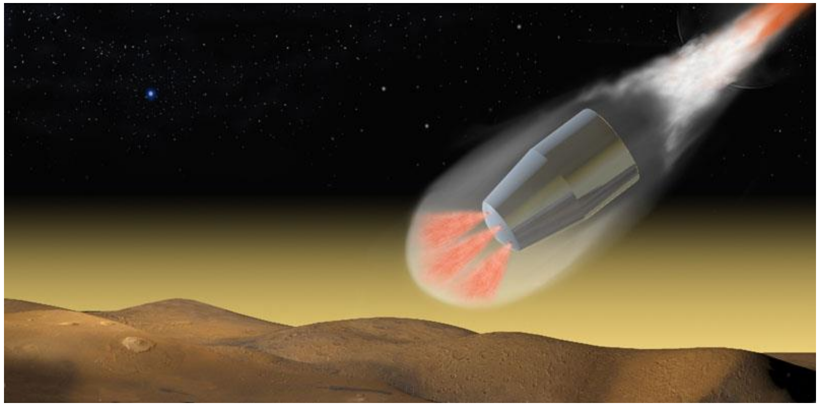


Large supersonic parachutes (D > 30 m)

Supersonic inflatable aerodynamic decelerators (SIAD)



Adaptable Deployable Entry and Placement Technology (ADEPT)



Supersonic Retropropulsion Technology

New EDL technologies will require validation of models for aerothermal, radiation, and TPS material response

Concluding Remarks

- Aerothermal modeling is inherently entwined with TPS design
- Aerothermal, radiation, and TPS material response are coupled so it’s important to check modeling assumptions
- Validation of numerical models using ground and flight tests is important to quantify uncertainties
- A margin policy based on statistical methods may provide greater insight in the key drivers and overall reliability of the design